^{4}He Experiments near T_λ in a Low-gravity Simulator

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We report on our latest measurements of gravity reduction in the low-gravity simulator. We made these measurements using a new thermal conductivity cell design that is 0.5cm in diameter and 0.5cm in height. Gravity reduction was verified by measuring both the reduction in the T_λ variation across the cell and the suppression of thermal convection as a function of the magnetic field. Full gravity cancellation was achieved in the simulator with $B(dB/dz) \approx 21$ T^2/cm, agreeing well with the calculated value and the valve found from levitating drops of helium.

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1. INTRODUCTION

Conventional ground-based ^{4}He experiments can experience limitations that are no longer imposed by insufficient temperature resolution, but rather by gravity. In a sample cell with a finite height, gravity induces a hydrostatic pressure that results in a variation in the superfluid transition temperature (T_λ) of about 1.273 μK per cm of vertical height. It was observed in 1g that sufficiently close to the transition the normal and superfluid phases coexist with the normal fluid being below the superfluid fluid with a distinct boundary between them.[1] This sets a limit on how closely the transition can be approached in the 1g environment without entering the two-phase state. To alleviate this limitation, a low-gravity simulator has been built in our laboratory to counteract gravity in a ^{4}He sample. It was proposed that ^{4}He could be levitated without changing the physics of the phase transition at T_λ.[2] Earlier measurements in our simulator have demonstrated a reduction
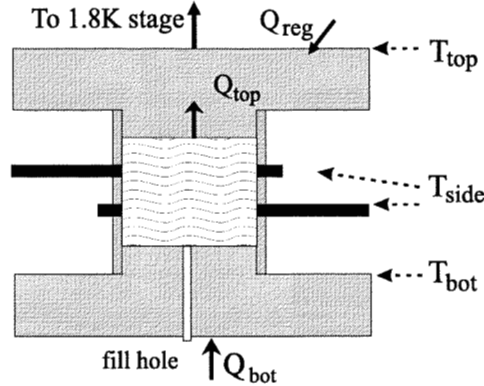
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Fig. 1. Schematic of the sample cell. The cell temperatures can be monitored using ^{4}He melting curve thermometers at four locations indicated by the dotted arrows.

of gravity.[3] Full levitation of liquid helium drops was recently visualized using a magnet similar to ours.[4] In the following, we report on our latest experiments that extended those earlier measurements to achieve full gravity cancellation in our simulator. This experiment verified that the magnet's performance meets the design specification and showed that the effective gravity in the sample could be reversed using our simulator.

2. EXPERIMENTAL OVERVIEW

The low-gravity simulator consists of a cryostat and a superconducting magnet. The magnet was purchased from Oxford Instruments, and is capable of producing 17 Tesla at its center with a maximum $B(dB/dz) = 23$ T^2/cm. The magnet was operated in the persistent mode during our experiments. We constructed a new thermal conductivity cell that consists of annealed OFHC copper endcaps, Vepsel sidewalls, and two sidewall probes. A schematic of the cell is shown in Fig. 1. Each side probe is made of an annealed 0.002"-thick pure copper foil and is sandwiched between Vespel sidewall rings, and is located at 1/3 of the cell height from the respective endcap. The cell is glued together with epoxy. The glue joint between the sidewall and the top endcap was inspected under a microscope to ensure no gap existed. The inside of the cell was cleaned to ensure that the surfaces of the sidewall probes in contact with the liquid helium were free of epoxy. The cell is filled through a 0.013"-dia hole in the bottom endcap.

Temperatures were measured using ^{4}He melting curve thermometers (MCT) with a 6nK resolution and little dependence on the magnetic field.

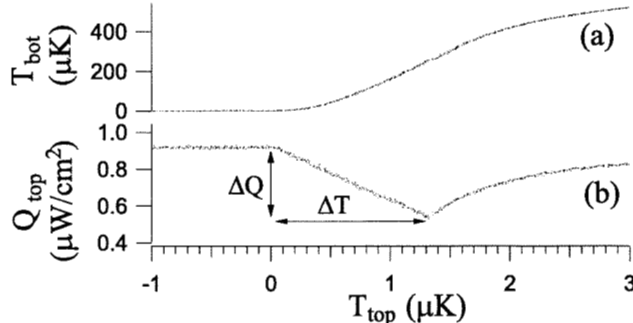## ^{4}He Experiments near T_λ in a Low-gravity Simulator

Fig. 2. T_{bot} (a) and Q_{top} (b) vs. T_{top} during a typical T_λ ramping run in the 1g environment. The ramp rate of T_{top} was 0.55nK/s and $Q_{bot} = 0.918\mu W/cm^2$. The temperatures are referenced to $T_\lambda^b \equiv 0$.

During the T_λ measurements, data was typically taken by starting the cell below T_λ, applying a known heat current to the bottom of the cell (Q_{bot}) and ramping the cell top temperature while monitoring the heat used to regulate the top of the cell (Q_{reg}). For the convection measurements, the temperature difference between the top and bottom of the cell was recorded for a known heat current applied to the bottom of the cell while the cell top temperature was held constant at $T_\lambda + 12$ mK.

3. RESULTS

Experimentally, we employed two independent methods to verify the reduction of gravity in the simulator. The first method measured the difference of T_λ at the cell top and cell bottom boundaries, which is linearly proportional to the hydrostatic pressure or the effective gravity in the cell. The second method measured the critical temperature, ΔT_c, for thermal convection. This critical temperature is inversely proportional to the effective gravity. We describe the details of these two methods below.

3.1. T_λ Measurements

The difference of T_λ, $\Delta T_\lambda = T_\lambda^t - T_\lambda^b$, was obtained by identifying T_λ^b and T_λ^t while slowly ramping up the cell top temperature with a constant heat current (Q_{bot}) applied to the cell bottom endcap.[3] One example measurement is shown in Fig. 2. Q_{top}, the heat current leaving the liquid helium into the cell top endcap, is obtained by $Q_{top} = Q_{bot} - \Delta Q_{reg}$. The signature of T_λ^b is the sudden increase in the bottom temperature T_{bot} due to the appearance of normal fluid at the cell bottom interface. At the same
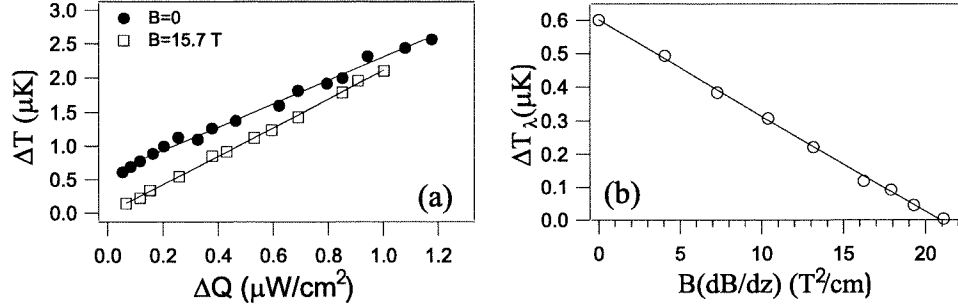
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Fig. 3. (a) ΔT vs. ΔQ (b) Reduction of ΔT_λ in the sample cell by the low-gravity simulator. The lines represent linear fits to the data.

time, Q_{bot} decreases due to the fact that part of Q_{bot} is used to increase the enthalpy of the normal fluid. T_λ^t is identified by the turning point in Q_{top} which corresponds to when the cell is full of normal fluid.

Accounting for the boundary resistance and the T_λ depression by a heat current, we get the relation:

$$\Delta T = La/g(1.273\mu K/cm) + R\Delta Q \tag{1}$$

where L is the cell height, a/g is the effective gravity, and R is the boundary resistance (R_b) plus the contribution due to the T_λ depression by a heat current. ΔT vs. ΔQ as defined in Eq. 1 and Fig. 2 are plotted in Fig. 3(a). $\Delta T_\lambda = La/g(1.273\mu K/cm)$ is then obtained by a linear extrapolation to $\Delta Q = 0$ at each applied field. The result for ΔT_λ is plotted in Fig. 3(b) as a function of $B(dB/dz)$ (T^2/cm). The typical error for ΔT_λ is $\pm 20 nK$. A linear fit to the ΔT_λ data yields $B(dB/dz) = 20.9 \pm 0.2$ (T^2/cm) for full gravity cancellation. This is in good agreement with the calculated value and the valve found in the liquid drop levitation experiments by Weilert et al.[4]

There are a couple of features that are worth mentioning. First, at zero field $(B = 0)$, $\Delta T_\lambda \approx 0.60\mu K$, which is within 5.5% of the value $L \times 1.273\mu K/cm$ expected using the approximated cell height $L = 0.5$ cm. This probably reflects uncertainty in the cell geometry. Second, the slope of ΔT vs. ΔQ, which is proportional to the thermal boundary resistance, increases with increasing magnetic field. This is probably due to the fact that the thermal conductance of the copper endcaps is suppressed in a magnetic field,[5] but it is possible that the Kapitza resistance could also be a function of the magnetic field.
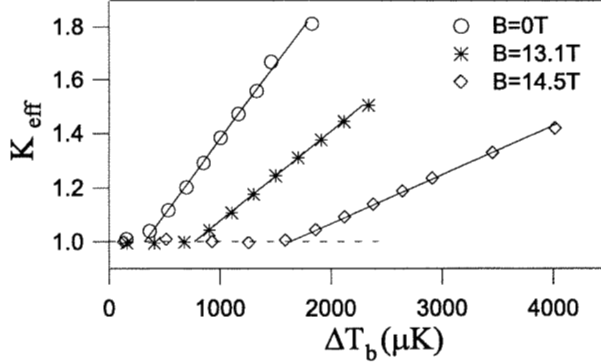
Fig. 4. K_{eff} *vs.* ΔT_b at three magnetic fields: $B = 0, 13.1,$ and 14.5 Tesla.

3.2. Convection Measurements

As a consistency check on the T_λ measurements described above, we also measured the critical temperature (ΔT_c) of thermal convection as a function of the magnetic field. During the measurements, the cell top temperature was fixed at 12mK above T_λ, a high enough temperature to have a positive isobaric thermal expansion coefficient (α) and relatively small temperature variations in α, the thermal diffusivity κ, and the kinematic viscosity ν.[6] Due to the finite thermal conductivity of the normal fluid, a temperature difference between the top and bottom endcaps (ΔT_b) is established when a heat current Q_{bot} is applied to the bottom endcap. To characterize the convection, we define the effective thermal conduction, K_{eff}, as the ratio of total conduction over the conduction of the conduction state before the onset of convection. $K_{eff} \equiv 1$ when $\Delta T_b < \Delta T_c$ and $K_{eff} > 1$ when $\Delta T_b > \Delta T_c$. The representative results are plotted in Fig. 4. It clearly shows that the critical temperature increases with increasing magnetic field due to a reduction of the effective gravity, as shown in Fig. 5(a).

For a fixed geometry and assuming the Boussinesq approximation, the critical Rayleigh number Ra_c is a constant and is defined as

$$Ra_c = \frac{\alpha \Delta T_c L^3}{\kappa \nu} a \qquad (2)$$

All of the fluid parameters in Ra_c are evaluated at the temperature of the cell mid-plane. In Fig. 5(b), we plot a quantity that is related to Ra_c, $\gamma \equiv (\kappa_0 \nu_0 / \alpha_0)(1/\Delta T_c)$. This quantity is linearly proportional to the effective gravity a/g, where $(\kappa_0, \nu_0, \alpha_0)$ are (κ, ν, α) normalized by their values at the cell top temperature ($T_\lambda + 12$ mK). With full gravity cancellation, ΔT_c becomes infinite or γ becomes zero. Linear extrapolation to $\gamma = 0$ yields

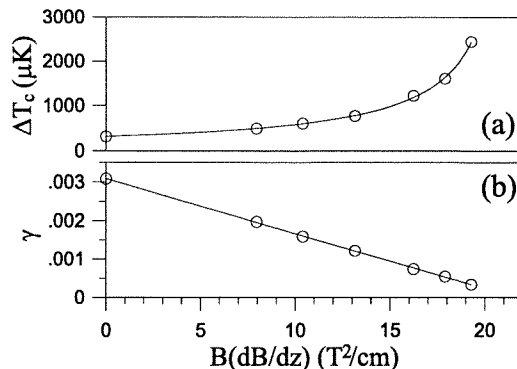**Y. Liu, M. Larson, and U. Israelsson**

Fig. 5. (a) ΔT_c and (b) γ (defined in the text) *vs.* $B(dB/dz)$. The solid lines are the fits to the data.

$B(dB/dz) = 21.6 \pm 0.1$ (T^2/cm) for the full cancellation, which agrees with but is slightly higher than the value obtained from the T_λ measurements. This is not surprising because at very large ΔT_c linear extrapolation breaks down, and the linear approximation overestimates the value of $B(dB/dz)$ due to a slight decrease in Ra_c.[7]

4. CONCLUSION

We have verified the reduction of gravity in the low-gravity simulator by measuring both the reduction in the T_λ variation across the cell and the suppression of thermal convection as a function of the magnetic field. Full gravity cancellation was achieved with $B(dB/dz) \approx 21$ T^2/cm. The performances of the simulator have been proven to meet the expectation.

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